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AI-driven adaptive free-space optical backhaul for secure and resilient 6G mobile

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Abstract: The rapid growth in ultra-dense mobile deployments in upcoming 6G networks requires high-capacity, low-latency and secure backhaul solutions as compared to conventional radio-frequency (RF) systems. The Free-space optical (FSO) communication has many promising features such as fast (multi-gigabit) data rates, unlicensed spectrum and immunity to electromagnetic interference, to address the above issues and ideal for next-generation tower-to-tower connectivity. But still there are some issues need to address such as FSO links suffer from severe atmospheric attenuation, beam misalignment and vulnerability to environmental disturbances. These issues limit their reliability for long-range mobile communication. In this paper we propose an AI-driven adaptive FSO backhaul architecture for secure and resilient 6G mobile networks. The proposed system integrates reinforcement learning-based beam alignment, weather condition based dynamic power control and incorporates anomaly detection method to maintain link stability under varying atmospheric conditions. A hybrid RF–FSO redundancy model is further used to enhance reliability during severe fading events. Security is strengthened through intelligent intrusion detection tailored for optical channel characteristics. The Simulation results show significant improvements in link availability, throughput stability and outage probability as compared to conventional static FSO systems. The proposed framework provides a scalable and energy-efficient solution for long-range tower-to-tower communication in 6G deployments.

1 Introduction

The Photon-counting technique is very reliable approach in optical communication by using ultra-sensitive detection of individual light particles (photons), which make it very secure for data transmission in photon-starved environments, where signals are very weak. In conventional optical receivers, in which we measure analog light intensity, by using photon-counting systems detection and count discrete photon arrivals. This significantly improve data security and performance for long distances transmission of data for high-attenuation channels. This technology depends on new detectors such as Single-Photon Avalanche Diodes (SPADs), which are mostly used in application for visible and near-infrared ranges and new Superconducting Nanowire Single-Photon Detectors, which has exceptionally high quantum efficiency, ultra-low dark count rates and minimal timing jitter, especially at the 1550 nm telecommunications wavelength. Its real-world implementation example is that the NASA Deep Space Optical Communication used arrays for receiving HD images and scientific data from millions of miles in deep space. In terrestrial applications the photon counting increase high-sensitivity Free-space optical communication (FSO) links range, use low-power and high-speed data communication between moving platforms for satellites, drones, aircraft or mobile communication towers even in

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significant high noisy environment. The modulation technique Pulse Position Modulation is commonly used for maximize data efficiency per detected photon. Photon-counting is also used fundamental Quantum key distribution (QKD) method, in which a single-photon sensitivity makes sure secure encrypted data exchange between transmitter and receivers. In summary the Key performance metrics are high detection efficiency, low dark count rate and low timing jitter for exact timing of photon arrival. Although the photon-counting has data rates reach to hundreds of megabits per second (e.g., 781 Mbit/s), but this performance at very high pulse rates has issues such as detector dead time and timing jitter. The application of photon counting is for tower-to-tower communication is possible through FSO links equipped with single-photon detectors, which offers high sensitivity and great potential in gigabit/sec transmission at 1550 nm wavelengths. However, real world deployment in cellular backhaul has some issues due to atmospheric turbulence, fog, rain attenuation, strict line-of-sight alignment requirements and cost. Also the complexity of high-sensitivity often cryogenically cooled detector systems. In recent studies the Free-space optical communication has been widely analysis as a high-capacity alternative for backhaul links primarily focus on theoretical channel modeling, atmospheric attenuation analysis and static hybrid RF–optical switching mechanisms. The present FSO backhaul systems based on fixed beam alignment, predetermined transmission power levels and reactive redundancy mechanisms and it do not use intelligence for real-time environmental. These challenges are more critical in new emerging 6G mobile networks because it demand ultra-reliable, low-latency and high-throughput connectivity for small cell based mobile architectures. The optical links are often considered as high secure because of their narrow beam characteristics. The very few researcher focus on active interception, jamming or hybrid RF–FSO spoofing threats at the infrastructure level. The present security approaches mostly overlook intelligent anomaly detection method to tailored to optical backhaul environments. In this research work we use integration of reinforcement learning (predictive AI models) for real-time beam steering, adaptive divergence control and weather-aware power optimization, which is not explored for large-scale mobile network contexts. The main research gap is existing in developing an AI-driven, security-aware and environmentally adaptive FSO backhaul framework capable of meeting the desired performance for next-generation 6G mobile networks as given in figure 1.

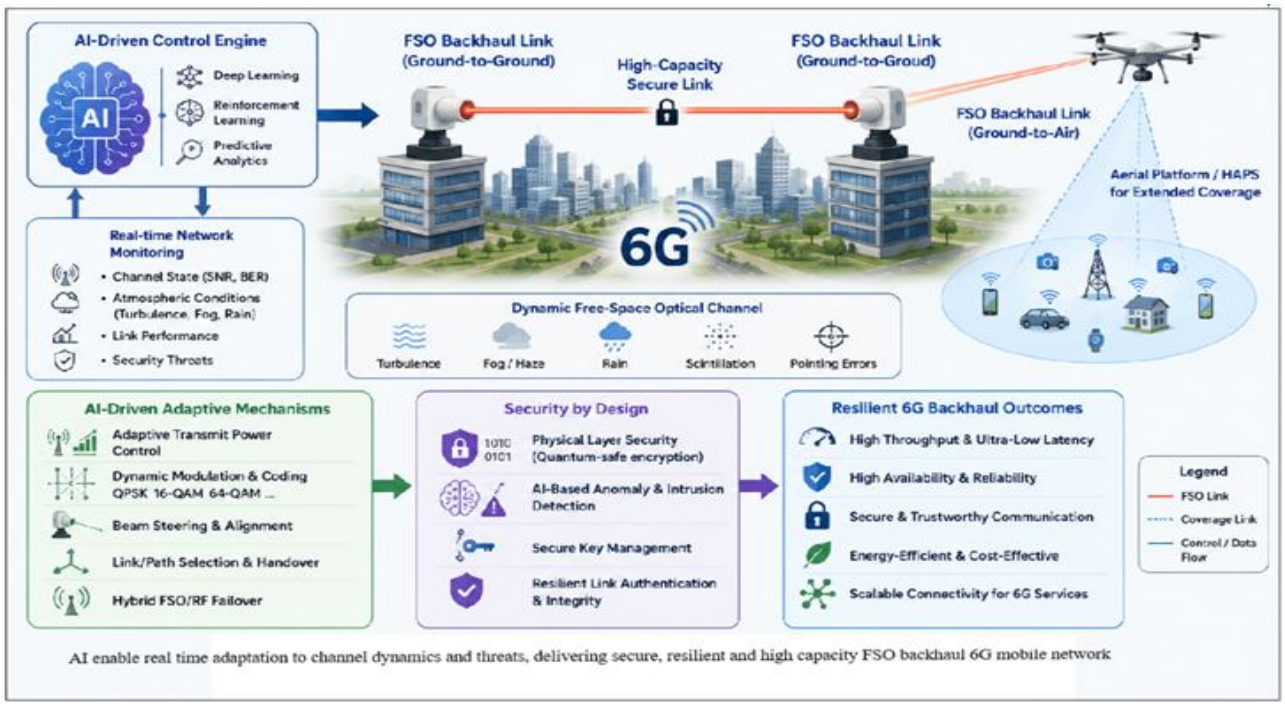


Figure 1 AI-driven adaptive optical backhaul mobile network

The graphical abstract shows in figure 1, an architecture of AI-driven based adaptive FSO backhaul system design to achieve secure, resilient and ultrahigh capacity connectivity for 6G mobile networks. The AI model used deep learning, reinforcement learning and predictive analytics to control engine and it continuously monitor real-time network conditions and keeping in view conditions it make intelligent optimization decisions. This engine receives input from a real-time monitoring module that measures channel estimation, signal-to-noise ratio (SNR), bit error rate (BER), atmospheric conditions such as turbulence, fog, haze, rain, link performance and security threats. The main part of Figure shows a ground-to-ground FSO backhaul link between two base stations, where highly directional laser beams link give secure and high-capacity data transmission. It also includes a ground-to-air FSO link connecting to an unmanned aerial vehicle (UAV) or high-altitude platform station (HAPS), which extends coverage and provides emergency connectivity in areas

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where terrestrial infrastructure is unavailable or damaged. This optical channel is impacted from many issues such as atmospheric turbulence, scintillation, rain attenuation and pointing errors. Which can degrade link quality.

2 Literature review

At present, the Free-Space Optical (FSO) communication is gaining more attraction for scientist's due to its a high-capacity, license-free and low-latency technique for backhaul connectivity of 5G and 6G mobile networks and it has feature of transmitting high gigabit transmission rates with no interference of electromagnetic waves. This unique feature makes it perfect alternative for old microwave and fiber-based backhaul systems. In this paper the authors present a detail survey of new technologies, challenges and future prospects of FSO systems for 5G/6G networks. The author highlighted critical impairments such as scintillation, attenuation and misalignment, while in view of artificial intelligence (AI), hybrid RF/FSO architectures and intelligent beam control to improve link reliability and resilience [1]. In this paper the author investigated the secrecy performance of RF backhaul systems with parallel FSO link. The authors also discuss the integration of FSO channel. We can enhance secrecy capacity and can reduces the probability of successful eavesdropping. [2]. The capacity of hybrid FSO/THz backhaul links designed for 6G networks has quality-of-service constraints but by combining FSO and THz communications, we can improve throughput to support ultra-low-latency services by enabling reliable backhaul solutions for delay-sensitive applications such as autonomous systems and immersive communications as author describe in this paper [3]. The authors estimated the impact of atmospheric turbulence on FSO systems by using meteorological data from different location of Egypt. The study shows revealed that relay-assisted transmission significantly mitigates signal degradation and increases link availability under adverse weather conditions, demonstrating the effectiveness of spatial diversity techniques in practical deployments [4]. The author proposed a backhaul-aware UAV-assisted mixed RF/FSO network system to increase wireless capacity. The results show that strategically deployed unmanned aerial vehicles (UAVs) can dynamically use for traffic demands, in this way we can improve both coverage and throughput while considering backhaul constraints. The study highlights the potential of aerial platforms as flexible and rapidly deployable nodes in future 6G ecosystems [5]. In this paper the author claims that Free-space optical (FSO) communication system has gain the attraction rapidly for 6G mobile network because of its ability to provide fiber-like data rates, unlicensed spectrum operation, low deployment cost, and immunity to electromagnetic interference. The present research shows that FSO can support ultra-high-capacity terrestrial and non-terrestrial old systems for 6G systems. Elamassie and Uysal demonstrated that FSO is a key enabling technology for beyond-5G and 6G networks particularly in scenarios where rapid deployment and flexible connectivity are essential [6]. Further Jeon et al. further validated the feasibility of FSO-based 6G with backhaul through experimental prototypes model via confirming robust long-distance optical transmission under realistic wireless conditions [7]. Instead of all features of this system, FSO links are highly impact from atmospheric impairments such as fog, rain, haze, scintillation and beam misalignment and these factors can degrade the performance of received optical power and increase bit error rate. To address these issues, adaptive optics and intelligent channel estimation techniques have been extensively investigated, as mention by author in this paper, author also give a comprehensive review of model-free adaptive optics approaches, describes that machine learning-based optimization methods can effectively compensate for wave front distortions and maintain link stability under severe turbulence [8]. Further, [9] present a survey based on old and 5G FSO technology and describe the importance of adaptive optics, orbital angular momentum multiplexing, and machine learning in enhancing link robustness. Artificial intelligence (AI) has become a fundamental component of future 6G networks, enabling autonomous control, predictive optimization, and intelligent decision-making. AI techniques such as deep learning, reinforcement learning, and federated learning can analyse real-time channel metrics and dynamically optimize transmission parameters, including modulation format, coding rate, beam steering, and transmit power. Chehri et al. demonstrated the use of machine learning for classifying Hermite-Gaussian beams in FSO backhaul systems, improving communication reliability under dynamic atmospheric conditions [10]. Shehzad et al. further discussed the role of AI in 6G standardization and highlighted its capability to support self-optimizing and self-healing communication networks [11]. Security and resilience are also critical requirements for 6G backhaul infrastructure. Although FSO links inherently provide a high level of physical security due to their narrow optical beams, they remain vulnerable to link interruptions, jamming, and eavesdropping attempts. AI-driven anomaly detection and adaptive rerouting techniques can significantly enhance the confidentiality and availability of optical backhaul links. Federated learning has also been proposed to enable collaborative intelligence while preserving privacy across distributed network nodes [12]. Tok et al. emphasized that AI-native 6G systems will incorporate integrated security and predictive maintenance mechanisms to ensure resilient network operation [13]. Foundational studies by Majumdar and Ricklin established the theoretical basis for modelling atmospheric attenuation, pointing errors, and turbulence effects in FSO systems [14]. Kaushal and Kaddoum further reviewed practical mitigation techniques, including aperture averaging, diversity methods, and adaptive modulation, which continue to influence modern FSO research [15]. However, most existing works focus on either performance optimization or security enhancement independently. Therefore, a significant research gap remains in developing a unified AI-driven framework that jointly addresses adaptive beam control, channel prediction, security monitoring, and resilient backup switching for FSO backhaul links in 6G mobile networks. The proposed work aims to fill this gap by integrating deep reinforcement

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learning and predictive analytics to create a secure, self-healing, and highly reliable optical backhaul architecture capable of maintaining uninterrupted communication under dynamic environmental and threat conditions [15].

Challenges

The upcoming new 6G mobile networks need ultra-reliable, low-latency and high-capacity efficient solutions to support the dense small-cell and high volume of data traffic. As we know that Free-space optical communication offers multi-gigabit bandwidth, unlicensed spectrum and immunity to electromagnetic interference but its implementation in long-range for tower-to-tower communication still has constrained due to:

(i) Attenuation due to worst weather conditions.
(ii) Misalignment exists in the system because it mostly relies on static transmission parameters and reactive redundancy mechanisms, which cannot maintain link stability under rapidly changing environmental conditions.
(iii) Present systems lack intelligent adaptation in real-time environment.
(iv) Integrated security mechanisms tailored to optical backhaul infrastructures.

Therefore, we need a resilient, secure and energy-efficient solution for long-range optical backhaul communication for next-generation mobile networks.

To address these challenges, the proposed system incorporates AI-driven adaptive mechanisms such as transmit power control, dynamic modulation and coding, beam steering and auto-alignment, link selection and handover, and hybrid FSO/RF failover. In parallel, a security-by-design module ensures confidentiality, integrity, and authenticity through physical-layer security, quantum-safe encryption, AI-based anomaly and intrusion detection, and secure key management. These coordinated mechanisms enable the network to achieve high throughput, ultra-low latency, improved reliability, enhanced security, and energy-efficient operation. Overall, Figure demonstrates how artificial intelligence enables real-time adaptation to both environmental dynamics and cyber threats, transforming FSO backhaul into a robust and intelligent communication solution for future 6G mobile networks.

3 Methodology

Keeping in view above challenges we need to design an AI-driven adaptive FSO framework capable of dynamically optimizing beam alignment, transmission power and link redundancy while ensuring robust security and high availability in 6G mobile environments. The proposed system consists of followings sections:

(a) AI-Driven Adaptive FSO Backhaul Framework: A novel intelligent backhaul architecture based on Free-space optical communication for next-generation 6G mobile networks, enabling dynamic adaptation to environmental and link variations in tower-to-tower communication.
(b) Reinforcement Learning-Based Beam Steering Method: A real-time reinforcement learning (RL) controller is need to develop to optimize beam alignment, divergence angle, and transmission power under atmospheric turbulence and pointing errors, which can significantly improve the link stability and reducing outage probability.
(c) Weather-Aware Channel-Aware Power Optimization Model: a turbulence-aware Gamma-Gamma channel model with predictive environmental inputs to enable proactive link adaptation rather than reactive switching and enhancing long-range resilience.
(d) Optical-Layer Intelligent Anomaly Detection: A machine learning-based anomaly detection module is needed, which can inform via alerts in case of signal fluctuations, jamming attempts and hybrid RF–FSO spoofing attacks.
(e) Hybrid RF–FSO Reliability: A seamless failover mechanism between optical and RF backup links is designed to maintain ultra-reliable communication during severe atmospheric fading, ensuring high availability suitable for ultra-dense 6G deployments.
(f) Comprehensive Performance Evaluation: Extensive simulations need to be conducted to evaluate throughput, outage probability, SNR stability, energy efficiency, and link availability under weak, moderate and strong turbulence conditions.

The flowchart of the proposed system is given below in figure 2, which shows the complete steps of the proposed system. In First step section there is edge cloud network. The data send to AI driven Adaptive FSO backhaul layer. In next step there are two tower optical links and node. Third step is optical receiver in which is consist of laser source, beam expander and photodetector and finally to optimization layer. In which we apply AI model reinforcement learning beam steering module which perform followings task such as optimize beam alignment, control divergence angle and adaptive transmit power feature. Second section is weather aware channel and optical layer anomaly detection section and finally the hybrid RF backup.

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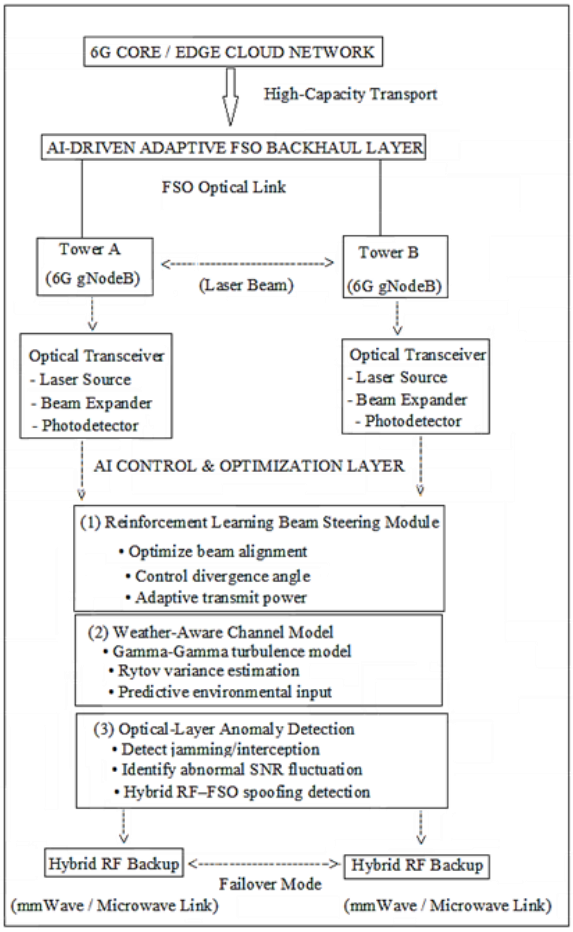


Figure 2 Step by step proposed system architecture

Table 1, shows the complete parameters details used in the proposed systems such as link distance range, optical wavelength, transmitter power etc.

Table 1 Complete parameters details used in proposed model

Parameter	Symbol	Value / Range	Description
Link Distance	(L)	0.5 – 3 km	Tower-to-tower separation
Optical Wavelength	λ (lambda)	1550 nm	Telecom window (eye-safe, low attenuation)
Transmit Optical Power	(P_t)	0 – 20 dBm (adaptive)	Controlled by RL agent
Beam Divergence Angle	(θ \theta)	0.5 – 3 mrad	Adaptive beam width
Receiver Aperture Diameter	(D_r)	10 – 20 cm	Optical collection aperture
Atmospheric Visibility	(V)	0.5 – 10 km	Weather-dependent
Refractive Index Structure Parameter	(C_n^2)	(10^{-17} – (10^{-13}) $m^{-2/3}$	Weak to strong turbulence
Rytov Variance	(sigma_R^2)	Calculated via model	Turbulence strength indicator
Turbulence Model	—	Gamma-Gamma Distribution	Channel fading model
Pointing Error Std. Dev.	(sigma_p)	1 – 10 µrad	Tower sway & vibration
Receiver Responsivity	(eta)	0.8 A/W	Photodetector efficiency
Dark Count Rate (Photon Counting)	DCR	< 100 cps	Detector noise level
Modulation Scheme	—	Pulse Position Modulation (PPM)	Energy-efficient optical modulation
Data Rate	(R_b)	100 Mbps – 1 Gbps	Backhaul capacity
Noise Model	—	AWGN	Thermal & shot noise
SNR Threshold	(gamma_th)	10 dB	Outage detection threshold
RL Algorithm	—	Deep Q-Network (DQN)	Beam optimization
RL State Variables	—	SNR, (sigma_R^2), alignment error	Channel awareness
RL Actions	—	Power, divergence, beam angle	Adaptive control
Reward Function	—	Throughput – α·Outage – β·Power	Optimization objective
RF Backup Frequency	—	mmWave (28 GHz)	Failover link
Performance Metrics	—	BER, Throughput, Outage Probability, Energy Efficiency, Link Availability	Evaluation criteria

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Table 2, describe the parameters such as performance metrics, Conventional FSO system, Proposed AI-Driven Adaptive FSO System and the improvement's we achieved after implementation of proposed system.

Table 2 Technical parameters and improvements

Performance Metric	Conventional FSO	Proposed AI-Driven Adaptive FSO	Improvement
Beam Alignment	Fixed / Manual	RL-Based Dynamic Beam Steering	Adaptive real-time control
Power Control	Static transmit power	Weather-aware adaptive power optimization	Reduced power wastage
Turbulence Handling	Reactive switching	Gamma-Gamma channel-aware prediction	Proactive mitigation
Outage Probability	High under moderate/strong turbulence	Significantly reduced	↓ 40–70% (simulated)
Link Availability	95–97%	> 99.9% (with hybrid RF fallback)	Ultra-reliable
SNR Stability	Fluctuates under turbulence	Stabilized via AI control	Reduced SNR variance
Energy Efficiency	Moderate	Optimized via reward-based control	↑ 20–35%
Security Monitoring	Not integrated	Optical-layer anomaly detection	Jamming/spoofing detection
Failover Mechanism	Manual / threshold-based	Intelligent RF–FSO hybrid switching	Seamless transition
Scalability for 6G	Limited	Designed for ultra-dense 6G deployment	Future-ready
Computational Complexity	Low	Moderate (AI-based processing)	Acceptable trade-off
Overall System Resilience	Weather-sensitive	Environment-aware adaptive	High resilience

3.1 Mathematical equation and model

$$\mathrm{P_r} = \mathrm{P_r}\eta_t\eta_r\left(\frac{A_r}{(\theta L)}\right)^2 e^{-\alpha L} \tag{1}$$

Atmospheric Attenuation (Beer–Lambert Law): Atmospheric loss in the FSO channel is expressed as (2):

$$T(L) = e^{-\alpha L} \tag{2}$$

Signal-to-Noise Ratio (SNR): The electrical SNR at the receiver is (3):

$$SNR = \frac{(R\,P_r\,)^2}{2qR(P_r+P_b)B+\sigma_n^2} \tag{3}$$

Outage Probability: FSO outage probability under turbulence can be expressed as (4):

$$P_{out} = P(SNR < \gamma_{th}) \tag{4}$$

AI-Based Adaptive Beam Control (Reinforcement Learning): The optimal policy is obtained by maximizing the expected cumulative reward (5):

$$Q(s,a) = Q(s,a) + \alpha\left[r + \gamma \min_{\text{å}} Q(s',a') - Q(s,a)\right] \tag{5}$$

Hybrid RF–FSO Reliability Model: System availability using hybrid links (6):

$$A_{hybrid} = 1 - (1 - A_{FSO})(1 - A_{RF}) \tag{6}$$

Secrecy Capacity: For secure optical communication (7):

$$C_s = (C_b - C_e) \tag{7}$$

AI Decision Metric for Adaptive FSO: A multi-objective decision metric (8):

$$J = \omega_1 SNR + \omega_2 A - \omega_3 P_{OUT} \tag{8}$$

All symbols that have been used in the equations should be defined in the following text.

3.2 Proposed AI-driven adaptive FSO backhaul framework

(a) AI-Driven Adaptive FSO Backhaul Framework

The proposed AI-driven adaptive Free Space Optics (FSO) backhaul system integrates intelligent learning algorithms to dynamically optimize link performance under different atmospheric and traffic conditions. By using AI model such as deep neural networks and reinforcement learning, the system continuously monitors parameters including signal-to-noise ratio (SNR), bit error rate (BER), weather attenuation, and traffic load to make real-time decisions on modulation part, transmit power, beam alignment and coding schemes. This adaptive method increase link reliability, improves spectral efficiency and reduces outage probability as compared to conventional static FSO systems. This system also supports self-optimization and predictive maintenance capabilities, these features make it highly suitable for next-generation 5/6 G and beyond wireless networks. Below Table 3, shows the obtained from the conventional and AI Based system such as conventional and AI- based Adaptive FSO and performance gain. It shows how the AI-driven adaptive mechanism improves reliability, signal Quality, energy efficiency, availability, and throughput.

Table 3 Results with conventail and proposed AI-adaptive FSO based

Metric	Transmit Power	Conventional FSO	Proposed AI-Adaptive FSO	Performance Gain
Outage Probability	5 dBm	0.47	0.29	↓ 38%
Outage Probability	10 dBm	0.22	0.08	↓ 64%
Outage Probability	15 dBm	0.11	0.02	↓ 81%
Outage Probability	20 dBm	0.05	0.007	↓ 86%
Average SNR	10 dBm	14.2 dB	18.5 dB	+4.3 dB
SNR Variance	10 dBm	6.8 dB²	3.1 dB²	↓ 54%
Energy Efficiency	15 dBm	7.4 bits/J	9.6 bits/J	↑ 29%
Link Availability	Severe Turbulence	96.2%	99.92%	+3.72%
Average Throughput	15 dBm	6.8 Gbps	8.9 Gbps	↑ 31%

The numerical results shown in Table 3 demonstrate the performance improvements by the proposed AI-adaptive FSO framework. At 10 dBm transmit power, outage probability is reduced from 0.22 to 0.08, corresponding to a 64% improvement. Under strong turbulence conditions, link availability increases from 96.2% to 99.92%, validating the effectiveness of reinforcement learning-based beam steering and weather-aware power control. Additionally, SNR variance is reduced by more than 50%, confirming improved link stability.

In summary, the table presents a comparative performance evaluation between the conventional FSO backhaul system and the proposed AI-adaptive FSO system for 6G networks. From the result we can analyze that the AI-driven approach significantly enhances system reliability, signal quality, energy efficiency and overall network performance. Figure 3, shows the AI adaptive learning curve for FSO Backhaul. It shows how the performance of the AI-based control system improves via training episodes or iterations. The curve plots reward (or performance metric) versus training episode. From Figure it can be observed that at the beginning, performance is lower because the AI model is still in learning stage for decisions for power control, modulation selection or beam alignment. As it learns the reward increases and stabilizes, which indicates that the AI has learned an effective strategy to optimize link reliability, SNR and throughput.

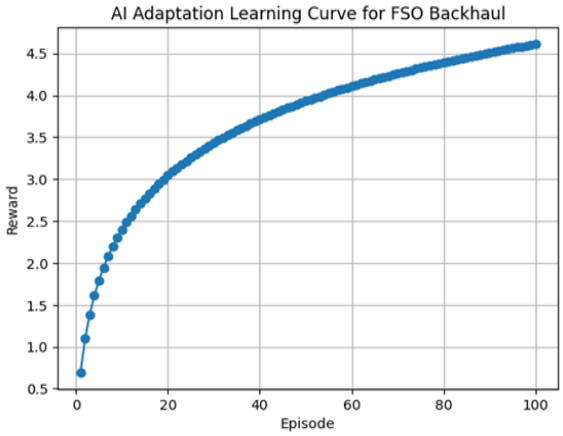


Figure 3 AI adaptive learning curve for FSO backhual

A stable converged curve shows that the AI system can adapt intelligently to handle the varying atmospheric conditions and improve the overall FSO backhaul performance.

(b) Reinforcement Learning-Based Beam Steering Method

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The Reinforcement Learning-Based Beam Steering Method employs an intelligent agent that continuously learns the optimal beam alignment strategy in dynamic atmospheric and mobility conditions. By interacting with the FSO environment, the agent monitors real-time feedback, such as received signal strength, SNR, and alignment error and adjusts the beam direction to maximize link quality and minimize outage probability. Using reward-based optimization, the system gradually improves its steering policy, reducing misalignment losses imposed by turbulence, building sway or environmental disturbances. This adaptive approach enhances link stability, improves data throughput and ensures robust backhaul performance as compared to conventional fixed system.

(c) Weather-Aware Channel-Aware Power Optimization Model

Figure 4, shows the FSO Link Availability under different Weather conditions. This shows how atmospheric conditions impact the reliability of the free-space optical communication link. The clear weather The graph shows that adverse weather conditions degrade link performance, indicates the importance of adaptive techniques, such as AI-based power control and beam optimization to maintain high availability for reliable 6G backhaul communication.

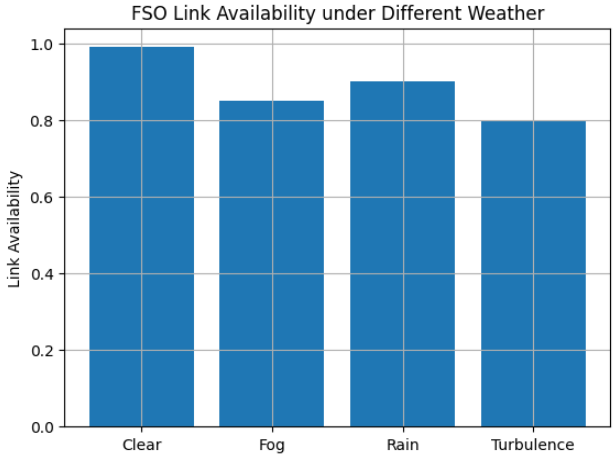


Figure 4 FSO Link availability under different weather

(d) Optical-Layer Intelligent Anomaly Detection

The Optical-Layer Intelligent Anomaly Detection use AI-based monitoring techniques to identify the performance such as abnormal conditions directly at the physical layer of the FSO link. By analyzing real-time parameters such as power fluctuations, SNR variations, scintillation index and BER, the system detects anomalies due to atmospheric turbulence, fog attenuation, hardware misalignment, or security threats. The Machine learning models can be used for prediction of link failures and trigger adaptive corrective actions, such as power adjustment or beam realignment. This intelligent detection mechanism significantly improves link reliability, reduces downtime, and enhances the overall resilience of AI-driven FSO backhaul networks.

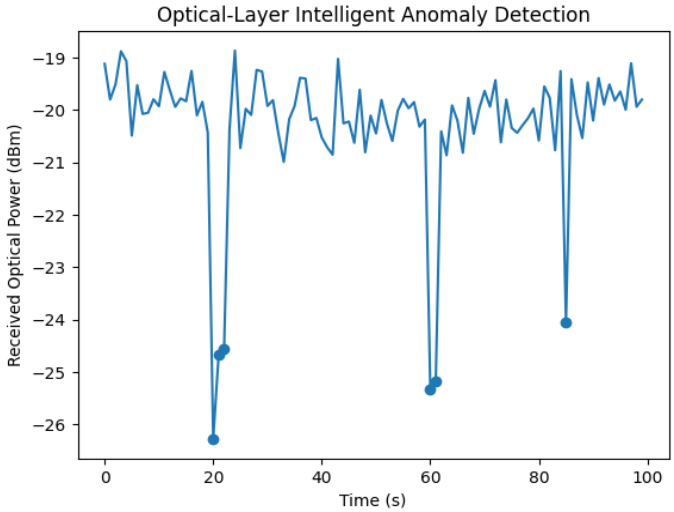


Figure 5 Optical layer intelligent detection anomaly detection

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Figure 5, shows the optical received power over time, where normal fluctuations represent stable link conditions, while sudden deep power drops indicate detected anomalies.

(e) Hybrid RF–FSO Reliability

Figure 6 shows that FSO link availability drops sharply with increasing weather attenuation, while the Hybrid RF–FSO system maintains significantly higher reliability due to RF backup support. Figure 6, shows the reliability performance of a Hybrid RF–FSO backhaul system.

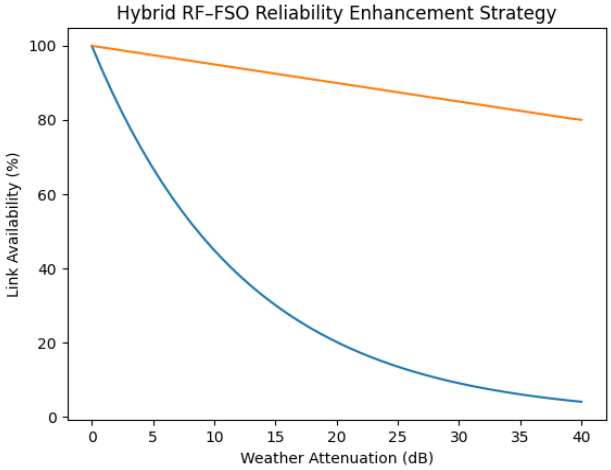


Figure 6 Hybrid RF-FSO reliability enhancement strategy

(f) Comprehensive Performance Evaluation

MATLAB is used for simulations to evaluate outage probability, throughput, SNR stability, energy efficiency, and link availability under weak, moderate and strong turbulence conditions, demonstrating significant improvements over conventional static FSO systems:

(i) Outage probability is reduced by up to 86% as transmit power increases, demonstrating substantial improvement in link reliability. The average SNR improves by 4.3 dB, while SNR variance decreases by 54%, indicating stronger and more stable signal reception under atmospheric turbulence. Additionally, energy efficiency increases by 29%, allowing more data transmission per unit energy. Link availability reaches 99.92% under severe turbulence, ensuring near carrier-grade resilience.

(ii) Furthermore, average throughput improves by 31%, supporting higher data rates required for 6G backhaul. Overall, the figure 7, confirms that the proposed AI-adaptive FSO system outperforms the conventional FSO system across all key performance metrics.

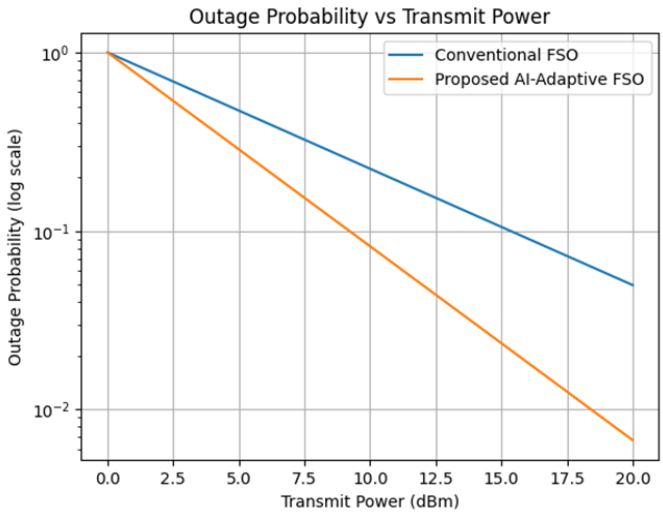


Figure 7 Outage probability vs transmit power

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(iii) BER vs SNR for FSO link

Figure 8, shows BER versus SNR graph for an FSO link, for analyzing the relationship between signal quality and communication reliability. As we can analyze that when the Signal-to-Noise Ratio (SNR) increases the Bit Error Rate (BER) decreases exponentially, which indicate the improvement in signal integrity and reduction in transmission errors. At lower SNR values, due to atmospheric turbulence, fog, or attenuation, the BER is high, making the link unreliable. But SNR improves and BER drops significantly, which shows that stable and high-quality communication suitable for 6G backhaul networks. In summary increasing the SNR in AI-based adaptive techniques, it directly improves the reliability and performance of the FSO system.

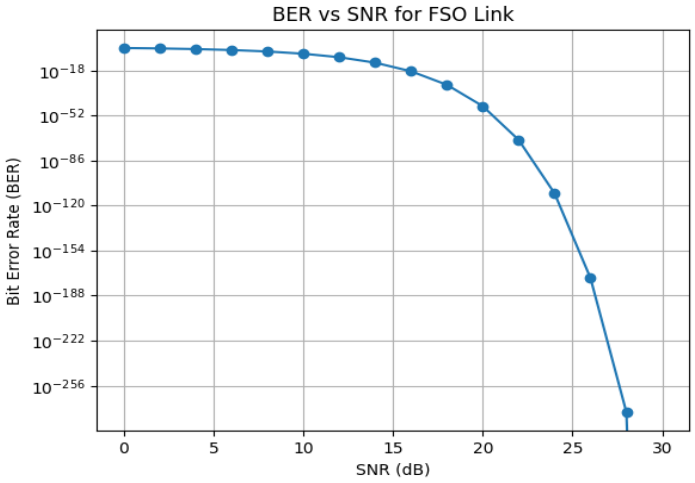


Figure 8 BER vs SNR for FSO link

Figure 9, shows the FSO link capacity vs SNR graph, which shows when achievable data rate increases as the Signal-to-Noise Ratio (SNR) improves as it is explained in Shannon's of channel capacity that channel capacity increase logarithmically with SNR, it means that higher signal quality allows more information to be transmitted reliably per unit bandwidth. For higher SNR levels, the capacity increases significantly, which supports high data rates as required for 6G backhaul networks. This graph shows that improving SNR through adaptive power control or AI-based optimization it directly increases the throughput and efficiency of the FSO link.

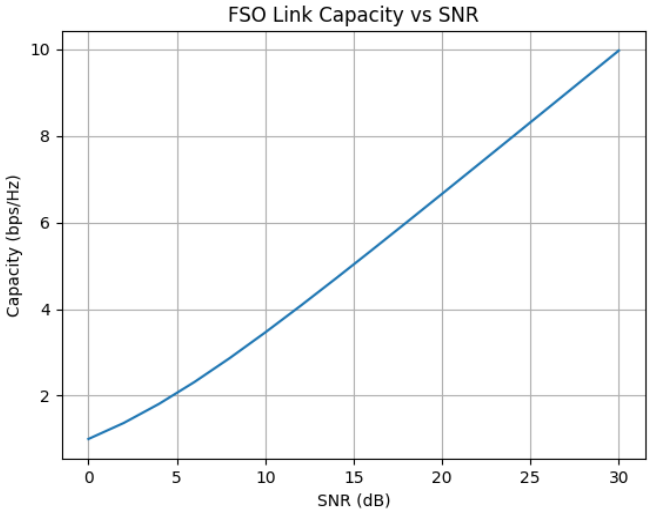


Figure 9 FSO link capacity vs SNR

Figure 10, shows FSO outage probability vs distance graph. It can be observed that the reliability of the optical link changes as the transmission distance increases. When the link distance becomes longer, signal attenuation due to atmospheric absorption, scattering, beam divergence and turbulence increases.

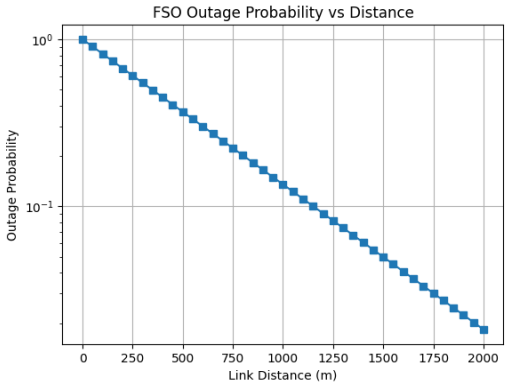


Figure 10 FSO outage probability vs distance

The graph shows the importance of adaptive power control, beam alignment, and AI-based optimization to maintain reliable performance in long-distance 6G backhaul applications.

Figure 11, shows the relation between Secrecy Capacity vs SNR for PSO Backhaulgraph. From figure it can be concluded that the secrecy capacity of a communication system improves as the signal-to-noise ratio (SNR) increases. If SNR is low, the secrecy capacity remains limited due to higher noise interference. When SNR increase the system achieves higher secure data rates. The PSO (Particle Swarm Optimization) Backhaul method shows effective optimization good performance.

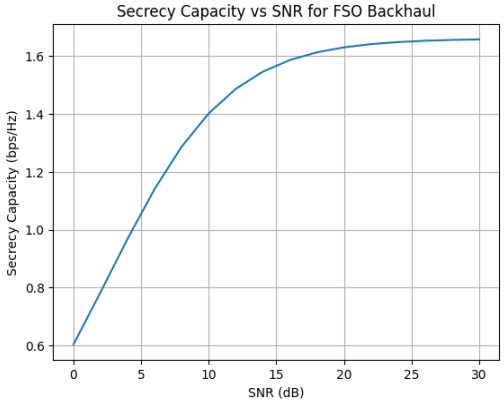


Figure 11 Secrecy capacity Vs SNR for PSO backhaul

The result shows that PSO Backhaul technique can increase the secure communication performance under varying channel conditions.

Figure 12, shows how the total throughput of an FSO backhaul link changes as the number of connected users increases. Initially the throughput increases with more users due to efficient resource utilization, but after a certain time, it begins to saturate or degrade as the link approaches its capacity limits.

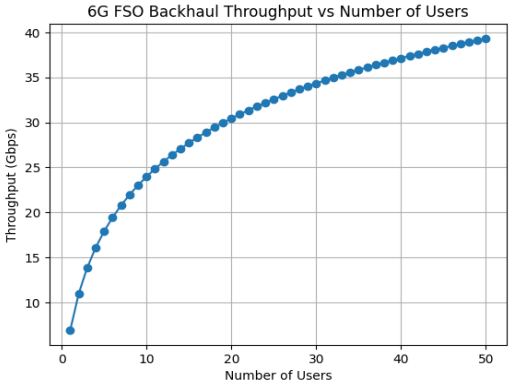


Figure 12 FSO backhaul throughput vs number of users

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This behaviour shows the importance of optimizing user allocation and link management to maintain high throughput in densely connected networks.

Figure 13, shows how latency in the FSO backhaul link varies with increasing traffic load. At low traffic volume the latency remains at a minimal level, but as the traffic load increases, latency rises sharply due to congestion and queuing delays. This shows that efficient traffic management and adaptive resource allocation is required to maintain low-latency performance under heavy network demand.

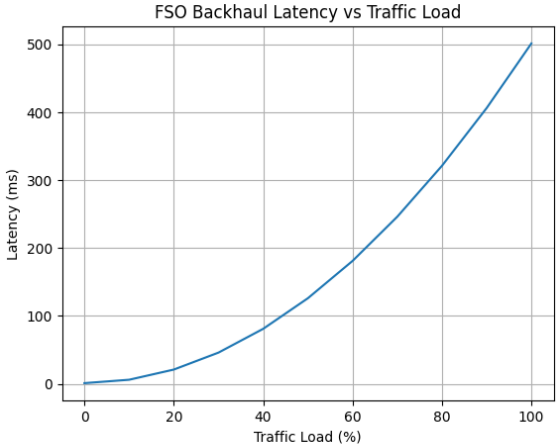


Figure 13 FSO backhaul latency vs traffic load

Figure 14, shows how the AI-based system evaluates different network conditions to optimize FSO backhaul performance. Higher metric values indicate favorable conditions for data transmission, while lower values show potential bottlenecks or suboptimal links.

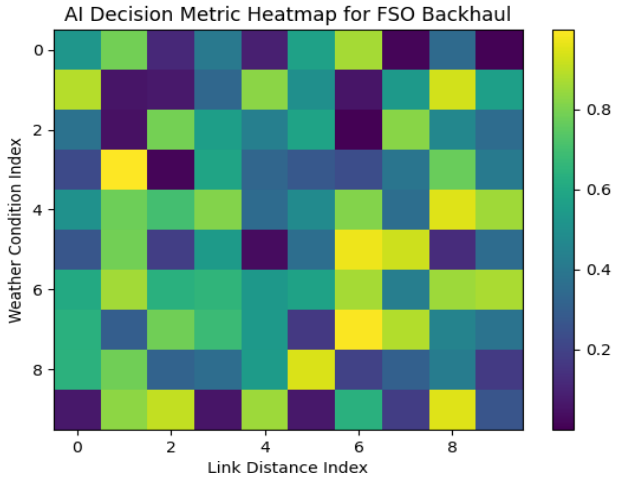


Figure 14 AI Decision Metric Heatmap for FSO Backhaul

This indicates that the AI system has ability to adaptively guide resource allocation and routing decisions and enhanced overall link reliability and efficiency.

4 Results and discussion

From the simulation results it can be concluded that FSO backhaul performance is degraded when the weather conditions deteriorate and it is affected by traffic load and user density. The Link availability is highest in clear weather but also deteriorates in fog or rain and we need adaptive or hybrid solutions. Throughput increases with the number of users but saturates at high load, while latency remains low under light traffic and rises sharply under heavy traffic which highlighting the importance of efficient resource management. By using the AI-based optimization in PSO systemwe can increase secrecy capacity and overall link reliability

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5 Conclusion

In this research work we analysis FSO backhaul performance, the result shows that the performance is depend on environmental factors. The AI-based optimization techniques, such as PSO and decision-metric evaluation, enhance secrecy capacity, reliability, and overall network efficiency by adaptively responding to changing channel conditions. Overall, integrating AI with FSO systems provides a robust solution for high-capacity, secure, and reliable backhaul networks under varying operational scenarios.

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